Fermilab

Particle Physics Division

Mechanical Department Engineering Note

Number: MD-ENG-200 Date: November 12, 2009

Project: Lab 3 cleanroom inert gas system, ODH analysis

Project Internal Reference: PPD/TC/Lab 3

Title: **ODH analysis for Lab 3 cleanroom**

Author(s): Russ Rucinski

Reviewer(s): Kurt Krempetz, Nov. 20, 2009

Key Words: ODH, Safety, Lab 3, cleanroom

Abstract/Summary:
This is an ODH analysis showing that the Lab 3 cleanrooms are ODH class 0. The area boundary is commonly referred to cleanroom A and cleanroom B. The inert gas source is gas phase generated by a 180 liter dewar that resides outdoors.

Applicable Codes: Fermilab Environment, Safety, and Health manual, chapter 5064 and 5064TA, rev. 5/09

ODH analysis for the clean rooms at lab 3

Result:
The ODH classification is class 0. No special precautions are required.

The highest calculated fatality rate is **Ø=ΣPi*Fi = 1.7 x 10-9 hr^{-1}.** This fatality rate was calculated assuming that there is no ventilation.

Discussion
The interior cleanrooms generally referred to as cleanroom A and cleanroom B have an inert gas distribution system that utilizes liquid cryogen boil-off. Flow rates and volumes of the inert gas are described later in this note.

As a good engineering practice, an interlock box is part of the inert gas supply system. Inert gas flow is permitted to each room only when that room's air circulation system is operating. The cleanrooms are shown to be class 0 neglecting the interlock box.

Area Description

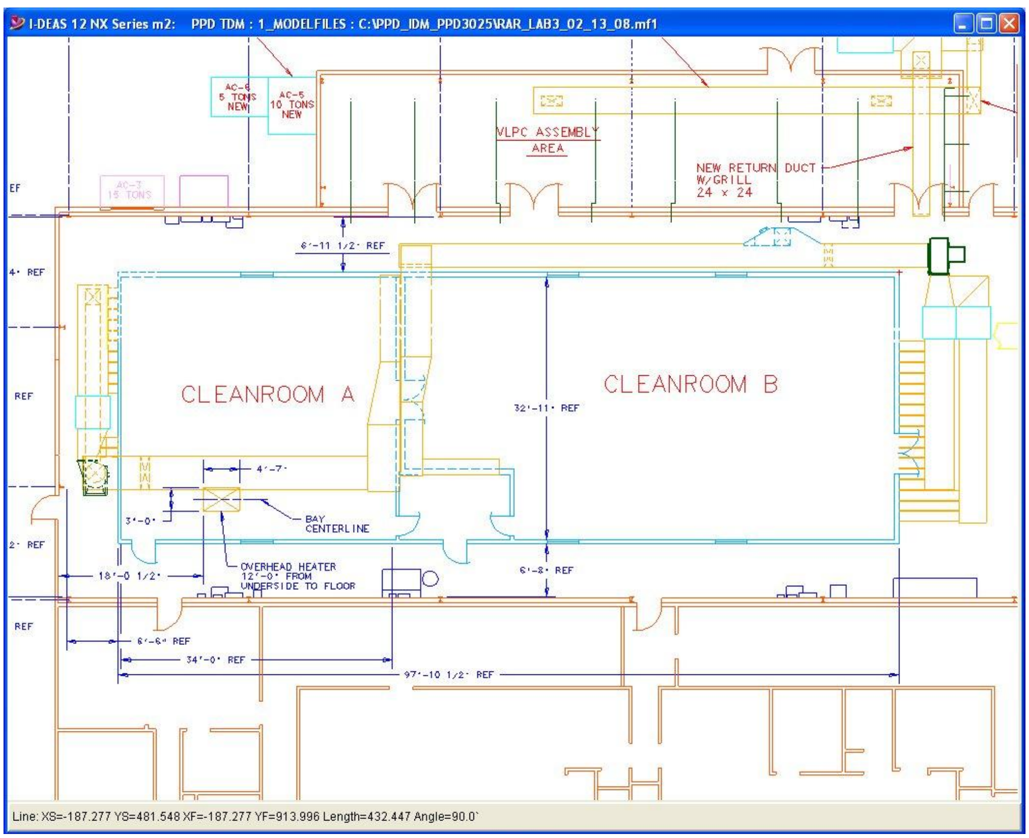


Figure 1. Plan view of cleanrooms A and B. Recirculation HVAC is shown.

Cleanroom A is 33' wide x 34.5' long x 12' high. It has a floor area of 1100 square feet and a volume of 13,860 cubic feet. Recirculated ventilation is provided by a blower mixing the air at a rate of approximately 27 room air changes per hour. Fresh air make-up is at least 325 cfm. The fresh air make-up was determined by measuring the air velocity at a fresh air intake grille and multiplying by the area (9" x 12") to give 330 cfm. The measurement was made on Nov. 12, 2009 using a Testoterm mini anemometer type 4400. Cleanroom A has a total ventilation rate (recirculated plus fresh air) of 6200 cfm. Measurements were made on Feb. 28, 2008.

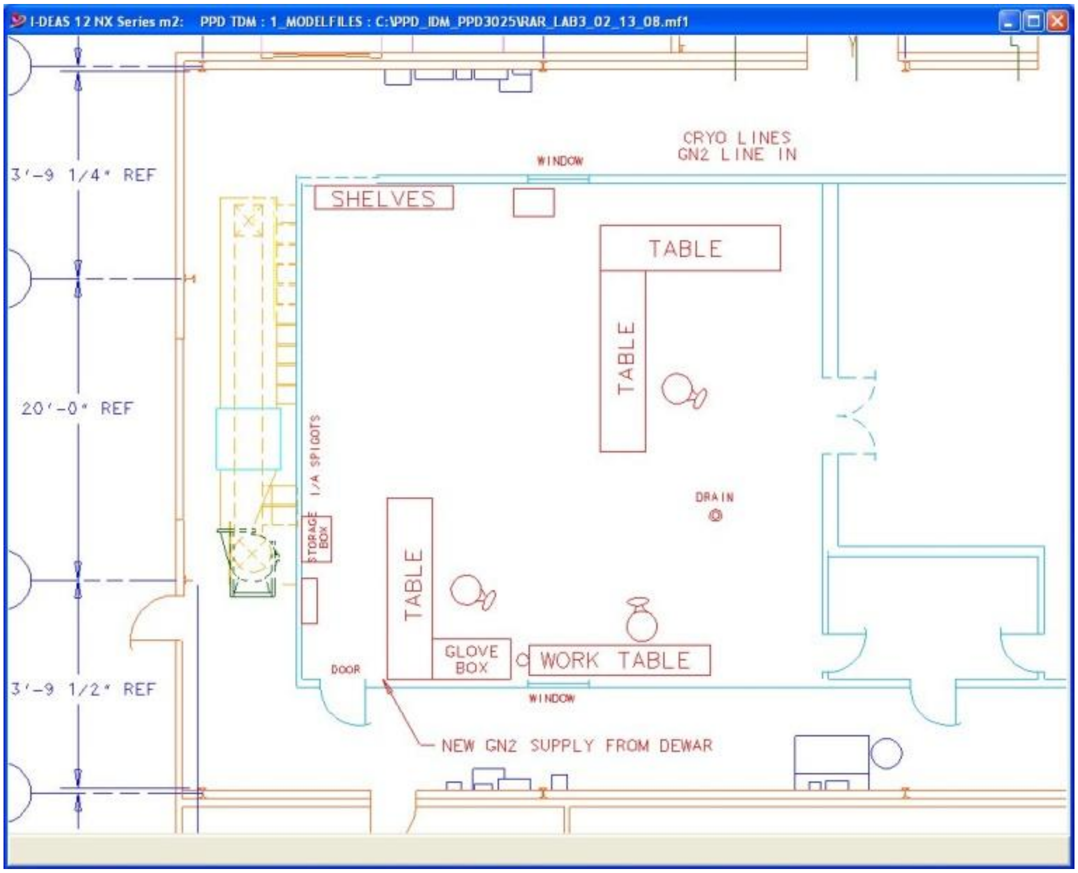


Figure 1. Cleanroom A. Also known as the north cleanroom.

Cleanroom B is 33’ wide x 62.7’ long x 12’ high. It has a floor area of 1900 square feet and a volume of 22,800 cubic feet. Recirculated ventilation is provided by a blower mixing the air at a rate of approximately 23 room air changes per hour. Fresh air make-up make up was measured at an intake grill and is 800 cfm. Cleanroom B has a total (recirculated plus fresh air) ventilation rate measured at 9600 cfm.

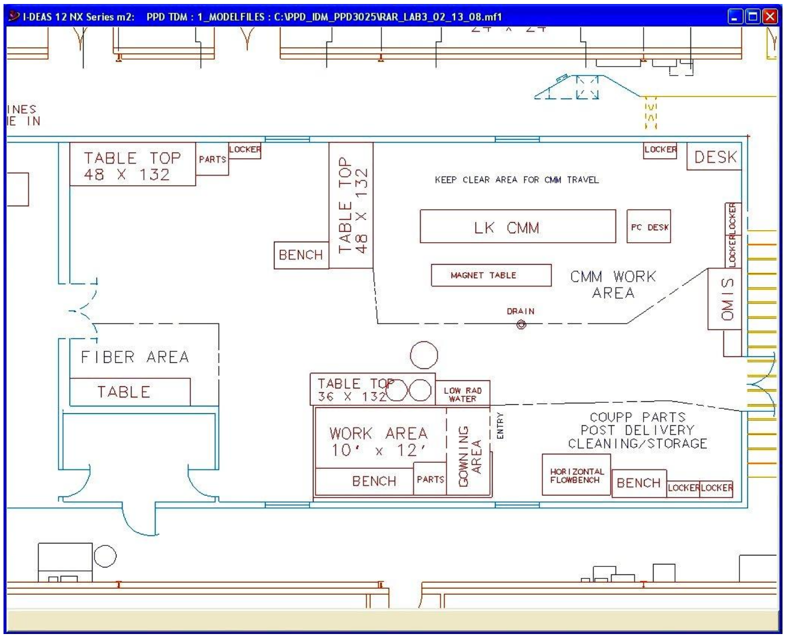


Figure 2. Cleanroom B. Also known as the south cleanroom.

Inert Gas Sources

Inert nitrogen or argon gas is supplied to both cleanrooms for purging materials and detectors that are sensitive to radon gas. Boil-off from these cryogenic liquids is low in radon concentration. The inert gas source is a 160 liter or 180 liter liquid nitrogen or argon dewar, located outdoors, near the gas bottle storage area at the south end of the building. Only one type of gas, nitrogen OR argon is used. Only one liquid dewar is connected at any time. As a back-up system, each cleanroom also has a single compressed gas cylinder that supplies gas if the pressure drops below 15 psig.

The liquid nitrogen dewar is FNAL stock number 1980-200500. The description is: LIQUID NITROGEN, MINUIMUM PURITY 99.995 PCT., OUTLET FOR LIQUID WITHDRAWAL IS 1/2 IN. FLARE MALE FITT. 180 LITER 22 PSI DEWAR, NON -FLAMMABLE

A 180 liter liquid nitrogen dewar contains 180 liters * (687 gas STP/liquid @BP) * (0.1337 ft^3/3.785) = 4368 standard cubic feet nitrogen.

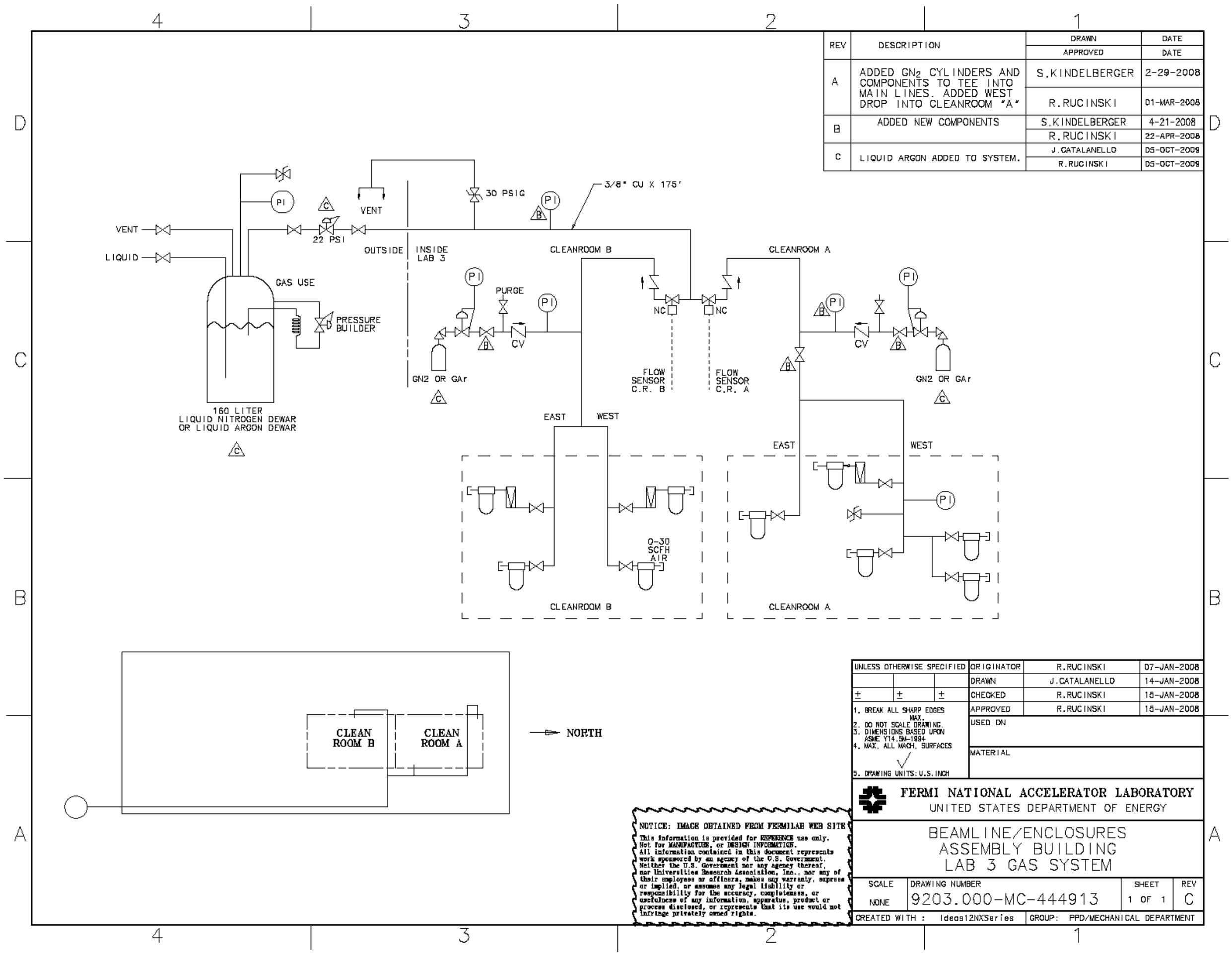


Figure 3: Inert gas system component flow diagram

A compressed gas cylinder of nitrogen contains <u>228 standard cubic feet of nitrogen</u>. The nitrogen is FNAL stock # 1980-120000. The description is: NITROGEN GAS, COMPRESSED, PRE-PURIFIED, MINIMUM PURITY 99.995%, CGA 580 FITTING, 2265 PSIG AT 70 DEG., <u>228 SCF</u> CYLINDER SIZE, NON-FLAMMABLE.
The total gas inventory = 4368 scf + 228 scf = **<u>4596 scf nitrogen</u>**.

Or, if we are using the system for argon;

The liquid argon dewar is FNAL stock number 1980-190500, LIQUID ARGON, MINIMIN PURITY 99.997PCT., OUTLET FOR LIQUID WITHDRAWAL IS 1/2 IN., FLARE MALE FITT. 180 LITER, 230 PSI DEWAR, NON-FLAMMABLE.

A 180 liter liquid argon dewar contains 180 liters * (687 gas STP/liquid @BP) * (0.1337 ft^3/3.785) = <u>5462 standard cubic feet argon</u>.

A compressed gas cylinder of argon contains <u>248 standard cubic feet of nitrogen</u>.The argon is FNAL stock # 1980-108000, ARGON GAS, COMPRESSED, IND.

GRADE, MINIMUM PURITY 99.995 PCT. CGA 580 FITTING, 2400 PSIG AT 70 DEG., 248 SCF CYLINDER SIZE, NON-FLAMMABLE

The total gas inventory = 5462 scf + 248 scf = **5710 scf argon**.

ODH Classification methodology

The safety analysis methodology that will be followed is Fermilab's safety and health manual chapter on Oxygen Deficiency Hazards, FESHM 5064 revision May 2009. Sections of this chapter are excerpted below.[i]

> The oxygen deficiency hazard fatality rate is defined as:
>
> $$\phi = \sum_{i=1}^{n} P_i F_i$$
>
> where $\varnothing$ = the ODH fatality rate (per hour),
>
> P_i = the expected rate of the i^{th} event (per hour), and
>
> F_i = the probability of a fatality due to event i.
>
> The summation shall be taken over all events~~,~~ which may cause oxygen deficiency and result in fatality. The value of F_i is the probability that a person will die if the i^{th} event occurs. The value depends on the oxygen concentration. If the lowest oxygen concentration is greater than 18%, then the value of F_i is zero, that is, all exposures above 18% are defined to be "safe" and to not contribute to fatality. It is assumed that all exposures to 18% oxygen or lower do contribute to fatality and the value of F_i is designed to reflect this dependence. If the lowest attainable oxygen concentration is 18%, then the value of F_i is 10^{-7}. This value would cause f to be 10^{-7} per hour if the expected rate of occurrence of the event were 1 per hour. At decreasing concentrations, the value of F_i should increase until, at some point, the probability of fatality becomes unity. That point was selected to be 8.8% oxygen, the concentration at which one minute of consciousness is expected.

The worst ODH condition will occur when the inert gas has been flowing for the longest. Inert gas from the dewar would only flow until the dewar empties. The oxygen concentration at that time can be calculated. Then inert gas from the back up cylinder flows for a time and after that period the oxygen concentration can be calculated. A fatality factor can be assessed based on that final oxygen concentration. The probabilities of failure are multiplied by that fatality factor to yield the ODH fatality rate, Ø.

Maximum possible gas flow rates

A 0.375 inch OD copper tube carries the gas from the dewar outside along the inside of the east wall of the main building to the interlock control box located midway along the exterior of the east wall of the clean rooms. The tubing run is about 200 feet. The gas pressure at the dewar is 22 psig. The maximum flow rate through 200 feet of 3/8" OD copper tubing is calculated to be 300 scfh = 5 scfm when the system is used for nitrogen. The maximum flow rate when we are using argon is 250 scfh = 4.2 scfm. The calculation of these flow rates is shown on page 4 of the attached hand calculations.

The back up gas cylinders are regulated to 15 psig at the cylinder valve and are connected with 32 feet of 0.375" OD tubing to a check valve and tee located at the interlock box location. The previous maximum flow calculation can be scaled by recognizing that flow rate is proportional to the square root of the absolute pressure and inversely proportional to square root of the tubing length. The average absolute pressure along the tubing length is used. When nitrogen is being supplied by the back-up cylinder, the flow rate is:

$$\frac{5\ scfm * \sqrt{(21.8\ psia * 200\ feet)}}{\sqrt{25.7\ psia * 32\ feet}} = 11.5\ scfm\ nitrogen$$

When argon is being supplied by the back-up cylinder, the flow rate is:

$$\frac{4.2\ scfm * \sqrt{(21.8\ psia * 200\ feet)}}{\sqrt{25.7\ psia * 32\ feet}} = 9.6\ scfm\ argon$$

Elapsed time of release

When using nitrogen, the dewar containing 4368 scf, divided by the maximum flow rate of 5 scfm yields the result that the dewar would run out in 874 minutes. The nitrogen back up cylinder would run out in 228 scf divided by 11.5 scfm = 20 minutes.

When using argon, the dewar containing 5462 scf, divided by the maximum flow rate of 4.2 scfm yields the result that the dewar would run out in 1300 minutes. The argon back up cylinder would run out in 248 scf divided by 9.6 scfm = 26 minutes.

Oxygen Concentrations after elapsed times and ODH classification

Normal Ventilation

It is first assumed that we have normal ventilation conditions with fresh air make up of Q = 330 cfm in cleanroom A and Q = 800 cfm in cleanroom B. The volume, V=13,860 cubic feet for cleanroom A and V=22,800 cubic feet for cleanroom B.

The oxygen concentration is given by FESHM 5064TA.

Case A During release - Ventilation fan(s) blowing outside air into the confined volume. Differential equation for the oxygen mass balance

(1)
$$V\frac{dC}{dt} = 0.21Q - (R+Q)C$$

Solution with the boundary condition of C=0.21 at t=0

(2)
$$C(t) = \left(\frac{0.21}{Q+R}\right)\left[Q + R\,e^{-\left(\frac{Q+R}{V}\right)t}\right]$$

Definitions

C = oxygen concentration

Cr = oxygen concentration during the release

Ce = oxygen concentration after the release has ended

Q = ventilation rate of fan(s), (cfm or m^3/s)

R = spill rate into confined volume, (scfm or m^3/s)

t = time, (minutes or seconds) beginning of release is at t=0

t_e = time when release has ended, (minutes or seconds)

V = confined volume, (ft^3 or m^3)

Cleanroom A, Nitrogen as a source gas. We have R = 5 scfm flowing for t=874 minutes and R=11.5 scfm flowing for t=20 minutes.

After the dewar has released its inventory, the oxygen concentration is:

$$C(874\ minutes) = \left[{}^{0.21}/_{(330+5\ scfm)}\right] * [330 + 5 * e^{-(335/13860)*874}]$$

The e^{-} term is 10E-9 and is therefore negligible. It is conservative to drop this term. It will be neglected for all remaining calculations.

C = 0.21 * [330/(330+5)] = 0.207 = 20.7%

After the backup cylinder is empty, the oxygen concentration is:

C = 0.207 * [330/(330+11.5)] = .1999 = **20.0 %.**

<u>Cleanroom A, Argon as a source gas.</u> We have R = 4.2 scfm flowing for t=1300 minutes and R=9.6 scfm flowing for t=26 minutes.

C = 0.21 * [330/(330+4.2)] = 0.207 = 20.7%

After the backup cylinder is empty, the oxygen concentration is:

C = 0.207 * [330/(330+9.6] = .201 = **20.1 %.**

<u>Cleanroom B, Nitrogen as a source gas</u>

C = 0.21 *[800/(800+5)] = .209 = 20.9% after the dewar empties and,

C = 0.209 *[800/(800+11.5)] = .206 = **20.6%** after the back up cylinder empties.

<u>Cleanroom B, Argon as a source gas</u>

C = 0.21 *[800/(800+4.2)] = .209 = 20.9% after the dewar empties and,

C = 0.209 *[800/(800+9.6)] = .206 = **20.6%** after the back up cylinder empties.

Table 1. Oxygen concentrations in cleanroom A & B for nitrogen or argon being used. Normal ventilation conditions.

	Nitrogen service	Argon service
Cleanroom A	20.0 %	20.1 %
Cleanroom B	20.6 %	20.6 %

All oxygen concentrations above 18% are considered safe. The probability of a fatality, Fi for oxygen concentrations greater than 18% is zero. Therefore regardless of the event that caused the release, the fatality rate is also zero.

Ø, $\phi = \sum_{i=1}^{n} P_i F_i$, Ø = 0.0 and the ODH classification is 0.

Oxygen Concentrations after elapsed times and ODH classification (continued)

Abnormal ventilation

As a second case to consider, what if the ventilation is not normal? The most likely scenario is a power outage. In that case, the normally closed solenoid valve in the interlock box would close stopping flow from the dewar. Only the back up cylinder volume could be released into the room. A release of 250 scfh of inert gas into the volume of the smaller cleanroom, A = 13,800 cubic feet, would result in an oxygen concentration of C = 0.21* [(13,800-250)/13,800] = 0.206 = 20.6%. Cleanroom B ends in a concentration of 20.8%. Since the oxygen concentration is above 18%, the ODH classification is 0.

What if the solenoid valve in the interlock box didn't close? The probability of a power outage is 1.0E-4 hr-1 and the failure rate of the solenoid to fail to close is 1.0E-3 per demand from FESHM 5064 table 2. So the probability of both a power outage and the solenoid failing to close is the multiple of those two numbers = Pi = 1.0E-7. In this case the fatality factor, Ø = summation of Pi*Fi would be less than or equal to 1.0E-7 hr^{-1} and the ODH classification is 0.

What if the belts on the recirculation fan break or the power to only the fans is disrupted? Even though there would not be forced ventilation, some mixed gas would exit the room through leaks. The room would initially be pressurized (it's normal state) but eventually would come to equilibrium with an exhaust rate at least equal to the incoming leak rate.

In this case, the oxygen concentration can be calculated as per case C in FESHM 5064. $C(t) = 0.21 * e^{-\frac{R}{V}t}$.

Cleanroom A, Nitrogen as a source gas. We have R = 5 scfm flowing for t=874 minutes and R=11.5 scfm flowing for t=20 minutes. V= 13,800 cubic feet.

After the dewar has released its inventory, the oxygen concentration is:

$C(t) = 0.21 * e^{-(5*874/13,860)} = 0.153 = 15.3\%$.

After the backup cylinder is empty, the oxygen concentration is:

$C(t) = 0.153 * e^{-(11.5*20/13,860)} = 0.150 =$ **15.0%.**

Cleanroom A, Argon as a source gas. We have R = 4.2 scfm flowing for t=1300 minutes and R=9.6 scfm flowing for t=26 minutes.
After the dewar has released its inventory, the oxygen concentration is:

$C(t) = 0.21 * e^{-(4.2*1300/13,860)} = 0.141 = 14.1\%$.

After the backup cylinder is empty, the oxygen concentration is:

$C(t) = 0.141 * e^{-(9.6*26/13,860)} = 0.139 =$ **13.9%.**

Cleanroom B, Nitrogen as a source gas

$C(t) = 0.21 * e^{-(5*874/22,800)} = 0.173 = 17.3\%$.

After the backup cylinder is empty, the oxygen concentration is:

$C(t) = 0.173 * e^{-(11.5*20/22,800)} = 0.171 =$ **17.1%.**

Cleanroom B, Argon as a source gas

$C(t) = 0.21 * e^{-(4.2*1300/22,800)} = 0.165 = 16.5\%$.

After the backup cylinder is empty, the oxygen concentration is:

$C(t) = 0.165 * e^{-(9.6*26/22,800)} = 0.163 =$ **16.3%.**

Table 2. Oxygen concentrations in cleanroom A & B for nitrogen or argon being used. Loss of ventilation condition where exhaust flow equals leak rate in. Partial pressure O_2

	Nitrogen service	Argon service
Cleanroom A	15.0 %, 112.5 mmHg	13.9 %, 104.3 mmHg
Cleanroom B	17.1 %, 128.3 mmHg	16.3 %, 122.3 mmHg

The probability of a fatality for oxygen concentrations are given in FESHM 5064 as presented in the graph below. In the graph below,135 mmHg oxygen partial pressure corresponds to 18%.

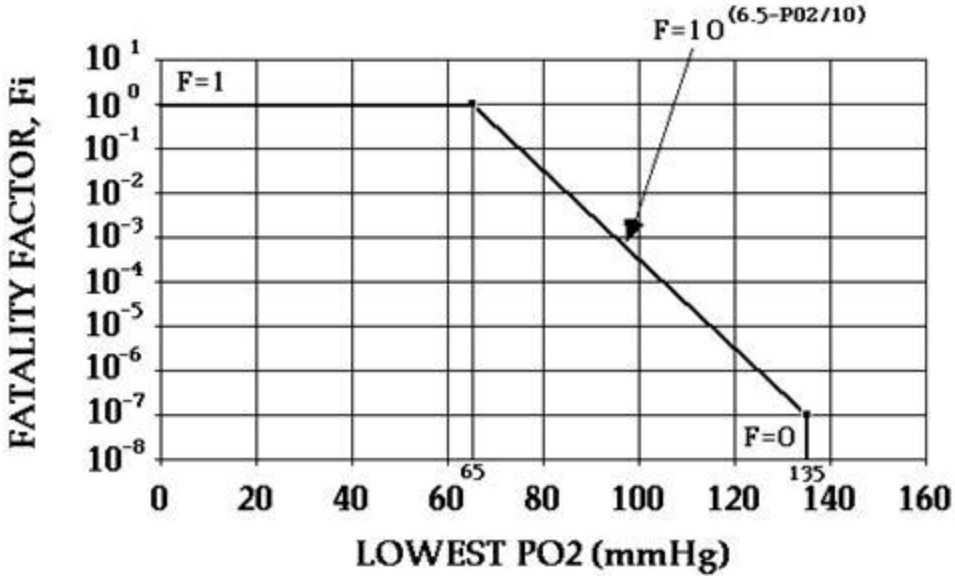


Table 3. Probability of Fatality, **Fi**, in cleanroom A & B for nitrogen or argon being used. This is the case of loss of ventilation where exhaust flow equals leak rate in.

	Nitrogen service, **Fi**	Argon service, **Fi**
Cleanroom A	1.8E-5 hr^{-1}	1.2E-4 hr^{-1}
Cleanroom B	4.7E-7 hr^{-1}	1.9E-6 hr^{-1}

Events and Probabilities

Recall that the only scenario that resulted in a non-zero probability of a fatality is when the ventilation fans are off due to a belt breakage, failure to start or run, etc. The probability of this can be estimated as a motor or pump that fails to start. Pi = 10E-5 hr^{-1} from FESHM 5064, Table 2. This probability of failure should be multiplied by the probability of any event that causes a release to arrive at the probability of both occurring at the same time. However, to be conservative and to not have to worry about maintenance periods on the fan, etc. I choose to change the probability of the fan being off to 1.0. This means that the fan could be off on purpose and this ODH analysis would still apply.

There are three events to consider that would lead to an inert gas release. Probability rates are from FESHM 5064 Table 2.

1.) The most likely event is operator error. An operator error of forgetting to re-close a valve is 1 in 100 (.01) per demand. The gas supply is normally used as a steady state purge of about 1 scfh (negligible in terms of ODH). I assume an operator would have an occasion to operate a valve once per month. That leads to a probability of release <u>Pi = 1.4E-5 hr^{1}</u>.

2.) Another event is the rupture or leakage of a valve or fitting. There are five or less valves per room and say 15 or less fittings for a total, N = 20 items. The probability of a rupture of a valve or fitting is 1E-8 hr^{1}. Multiplying that by 20 gives <u>Pi = 2 E-7hr^{1}.</u>

3.) The last event is the breakage and leakage of the tubing line. There are only two gas drops in the room. Each drop has a manifold. Let N = 4. The probability of a breakage or leakage of the tubing line is 10E-9hr^{1}. Multiplying by N, <u>Pi = 4E-9 hr^{1}</u>.

The flow rate for all these events is taken at worst case, maximum resulting in the probability of fatality as listed in Table 3. Since Fi is the same for each event it can be factored out of the summation.

$$Ø = \sum Pi * Fi = Fi * \sum Pi = Fi * (1.4 * 10^{-5} + 2 * 10^{-7} + 4 * 10^{-9})$$
$$= \mathrm{Fi} * (1.42 * 10^{-5})$$

With Fi taken from table 3, the result of the multiplication is the fatality rate, Ø. The values are shown in Table 4 below.

Table 4. Fatality rate, **Ø** in cleanroom A & B for nitrogen or argon being used. This is the case of loss of ventilation where exhaust flow equals leak rate in.

	Nitrogen service, **Ø**	Argon service, **Ø**
Cleanroom A	2.6E-10 hr^{-1}	1.7E-9 hr^{-1}
Cleanroom B	6.7E-12 hr^{-1}	2.7E-11 hr^{-1}

Result

The highest summed ODH fatality rate per hour is 1.7E-9. This is well below the ODH class 1 threshold of 1E-7 per hour and therefore the cleanrooms are ODH class 0. No special precautions are needed with regard to ODH.

Appendix 1.

Cleanroom A & B supply and return ventilation measurements

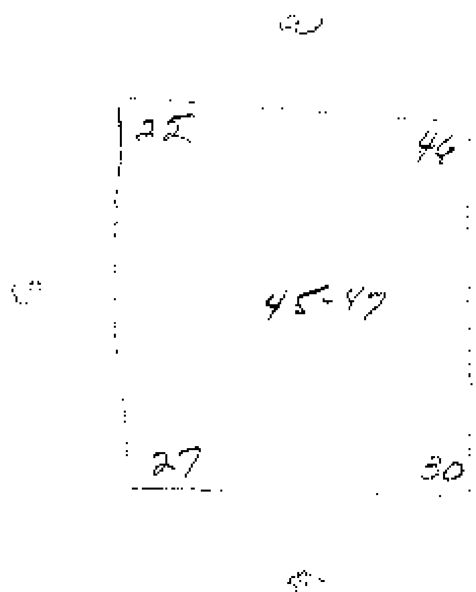
Clean room A		Supply grill dimensions:			Flow area	23 3/4" high X 14 5/16" wide	2.35	ft^2
					Cover	31 3/4" high X 53 1/4" wide		
Supply Air grills Left to right	Velocity Center	Velocity Top-Left	Velocity Top-Right	Velocity Bot-Left	Velocity Bot-Right	Velocity Average (feet/min)	Cubic feet per minute	
1	0	0	240	0	340	116	273	
2	340	290	430	380	300	348	818	
3	450	120	400	0	380	270	635	
4	230	340	0	470	260	260	611	
5	300	90	250	200	350	238	559	
6	430	90	240	300	180	248	583	
7	430	240	270	360	160	292	686	
8	420	320	210	430	150	306	719	
9	340	220	250	440	210	292	686	
10	350	120	190	250	340	250	588	
Units: Feet/minute						**Total=**	**6157**	**cfm**

Clean room A		Return grill dimensions:			Flow area	15 3/4" X 15 3/4" OD	1.72	ft^2
					Cover	13 3/8" X13 5/8" ID		
Return Air grills Left to right	Top-Left	Top-Right	Bot-Left	Bot-Right		Velocity Average (feet/min)	Cubic feet per minute	
1	400	710	530	230		467.5	804	
2	330	550	570	320		442.5	761	
3	230	520	380	560		422.5	727	
4	210	380	460	460		377.5	649	
5	200	420	780	400		450	774	
6	350	490	480	600		480	826	
7	410	640	690	620		590	1015	
8	400	600	650	800		612.5	1054	
						Total=	**6609**	**cfm**

Clean room B		Supply grill dimensions:			Flow Area	19 3/4" X 14 3/8" ID	1.97	ft^2
Supply Air grills Left to right	Center	Top-Left	Top-Right	Bot-Left	Bot-Right	Velocity Average (feet/min)	Cubic feet per minute	
1	0	0	0	80	90	34	67	
2	360	490	510	100	0	292	575	
3	410	420	440	410	80	352	693	
4	380	200	450	440	230	340	670	
5	450	240	440	400	330	372	733	
6	360	210	300	360	370	320	630	
7	600	400	NA	510	NA	503	992	
8	NA	NA	NA	NA	NA	0	0	
8.5	NA	NA	NA	NA	NA	0	0	
9	300	150	130	580	400	312	615	
10	400	190	330	420	350	338	666	
11	320	100	270	110	540	268	528	
12	180	150	100	110	110	130	256	
13	150	350	80	250	80	182	359	
14	400	180	360	320	230	298	587	
15	420	80	0	450	350	260	512	
16	410	90	NA	100	NA	200	394	
Units: Feet/minute		*Scaled to account for missing data				***Total=**	**9380**	**cfm**

Clean room B		Return grill dimensions:				15 3/4" 15 3/4" OD		
					Flow Area	13 3/8" X 13 5/8" ID	1.27	ft^2
Return Air grills Left to right	Top-Left	Top-Right	Bot-Left	Bot-Right		Velocity Average (feet/min)	Cubic feet per minute	
1	210	320	500	410		360	457	
2	210	190	400	330		283	359	
3	300	200	600	400		375	476	
4	390	280	560	470		425	540	
5	380	540	530	500		488	619	
6	440	530	560	280		453	575	
7	350	480	790	620		560	711	
8	510	560	460	200		433	549	
9	360	760	690	660		618	784	
10	590	780	620	430		605	768	
11	300	530	740	560		533	676	
12	380	620	850	700		638	810	
13	330	620	760	520		558	708	
14	420	660	760	610		613	778	
15	550	610	810	590		640	813	
						Total=	**9623**	**cfm**

MEASURENENTS MADE 10/28/09
BY SEAN WILSON.
CALCS BY RUSS RUCINSKI



DISPLAY × 10 = ft/MIN

≈ AVG ≈ 400 ft/min

VENT SIZE = $\frac{15 \times 20}{144}$ = 2.1 ft²

$\dot{Q} = V \cdot A = 400 \frac{ft}{min} \times 2.1\ ft^2 =$

= 800 cfm

USED TESTO TERM MINI-ANEMOMETER TYPE 4400
BORROWED FROM DØ BLDG. MANAGER

LAB 3 CLEANROOM FRESH AIR
MAKE-UP MEASURENTS

R. RUCINSKI
10-28-09

FERMILAB ENGINEERING NOTE	SECTION PPD/TC LAB 3	PROJECT LAB 3	SERIAL-CATEGORY 40.08.02	PAGE 4
SUBJECT INERT GAS FLOW TO CLEANROOMS		NAME RUSS RUCINSKI		
		DATE 10-12-2009	REVISION DATE	

CALC. FLOW RATE POSSIBLE TO CLEANROOMS.

3/8" OD Cu LINE × 175 ft., SUPPLY PRESSURE = 22 PSIG
+ BENDS, SOLENOID, VALVES ≈ 200 ft. EQUIVALENT.

$$\Delta P = 3.36 \times 10^{-6} \frac{f L W^2}{\rho d^5}$$

$$\Delta P = .000\ 000\ 007\ 26 \frac{f L T (q'_h)^2 S_g}{d^5 P'}$$ EQ. 3-5 CRANE TECHNICAL PAPER 410

$$(q'_h)^2 = \frac{\Delta P (d^5)(P')}{[7.26 \times 10^{-9}] f L T S_g}$$ RE-ARRANGED

$d = .375" - (.032")2 = .311$ in

$f = .03$ ESTIMATE

$S_g = .9672$ FOR N_2
1.377 FOR Ar

$L = 200$ FEET

$P' = 11$ psi $+ 14.3 = 25.3$ PSIA
AVG IN PIPE, ATM @ FNAL EL. 700'

$T = 68 + 460 = 528$ °R

$\Delta P = 22$ psi
$d^5 = .00291$

$q'_h = 270$ scfh N_2
OR
$q'_h = 226$ scfh Ar

CHECK Re#, f ASSUMPTION

$$Re = 0.482 \frac{q'_h S_g}{d \mu}$$ EQ. 3-3, CRANE TECHNICAL PAPER 410

$\mu = .017$ cp

$$Re = .482 \frac{(270)(.9672)}{(.311)(.017)}$$

$Re = 23{,}800 \longrightarrow$ TABLE PG. A-24, $\underline{f = .025}$

$$q'_h = q'_{h\ PREVIOUS} \times \sqrt{\frac{.03}{.025}} = 296 \text{ scfh } N_2,\ 248 \text{ scfh Ar.}$$